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# COMPARISON OF PREDICTED AND ACTUAL ORBITAL LIFETIMES FOR THE SEDS-2 MISSION

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## ABSTRACT

This paper documents a series of estimates of the orbital lifetime of the SEDS-2 flight configuration made prior to the mission. These estimates were made with program LTIME, which has been in use at MSFC for a number of years. Because of the unusual configuration of upper-stage/tether/endmass flown on this mission, and the type of assumptions and inputs used in LTIME, the effective area used in the drag calculation had to be estimated in an unusual way. The final pre-flight predicted lifetime was 28.35 days. In the actual flight, the tether was cut approximately 5 days into the mission. The instrumented endmass plus about 12 km of tether rapidly reentered the atmosphere, and the Delta II Second Stage plus the remaining 8 km of tether reentered on mission day 60. Tracking data was used to reconstruct reentry sequences for the two parts of the configuration after the cut. The predicted lifetimes for the endmass plus tether-fragment were in the range of 0.2 to 2.8 days, depending on the perigee altitudes assumed. The predicted lifetime of the upper-stage plus tether was 56.4 days, which corresponds to reentry on mission day 61, in good agreement with the actual reentry on day 60.

## INTRODUCTION

Prior to the flight of SEDS-2 we made predictions of the orbital lifetime so that mission options could be examined . As the mission orbit became better defined, these predictions were updated. During the actual mission the tether was severed, probably by a micrometeoroid or untracked debris, between Rev 74 and Rev 75 on March 15, 1994 [1]. Thus our lifetime prediction was rendered moot. After the tether was cut the endmass was no longer tracked, but the

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Delta II Second Stage was followed visually [2] and by radar [1] until it reentered on mission day 60. We have performed post-mortem lifetime "predictions" for the endmass plus 12 km of tether and for the upper-stage plus 8 km of tether, which we discuss below.

In the next section the prediction program and its required inputs are described. Then the methods used to estimate the effective areas for the drag calculations are discussed. The pre-flight input values and the resulting lifetime predictions follow. Subsequently, flight data is used to compare the post-mortem predictions with the actual events.

## LIFETIME PREDICTION PROGRAM

The program used to perform the lifetime predictions is LTIME. This program is descended from the program LIFTIM by Alford and Liu [3]. It uses Gauss-Legendre quadrature to numerically integrate the effects of drag and the Earth's oblateness on the orbit. The eccentricity of the orbit is used to characterize it, i.e., the orbit is considered circular if its eccentricity is less than 0.0005, and is considered elliptic if the eccentricity is greater than this. Different variables are integrated depending on the eccentricity. For circular orbits, equations for $da/dt$ and $d\Omega/dt$ are integrated. For the elliptic case, equations for $dr_A/dt$, $dr_P/dt$, $d\Omega/dt$, and $d\omega/dt$ are integrated. Here $r_A$ is the apogee altitude, $r_P$ is the perigee altitude, and the other variables are classical elements. Mean elements are used in all the computations except those for atmospheric density, which uses osculating elements so that a true altitude is obtained.

The density is computed from a simplified Jacchia 1970 model, which uses solar F10.7 index values and geomagnetic $a_P$ index values from tables specified by the user. These tables are arranged in the following catagories: Best Estimate, 2.3 Percentile, 97.7 Percentile, Plus One Sigma, Minus One Sigma, and Mean Cycle. From [4]:

> The 97.7 and 2.3 percentile envelope values for the current solar cycle [Cycle 22] are based on the statistical values obtained from the deviation between the observed and predicted values for the previous cycles [Cycles 9-21]. The best estimated curve for Cycle 22 is computed using a linear regression procedure and is also based on

Cycles 9-21. This curve is considered the most likely curve we would expect in the future based on the most recent observed data. Both the estimates and the inputs from the data base to the linear regression method represent smoothed values over a 13-month period. We also show data for a mean cycle which is the statistical mean of the previous Cycles 9-21 and does not represent any confidence implication of our projection.

In making our lifetime predictions for the SEDS-2 mission we have consistently used Best Estimate index values.

Besides the activity indices just mentioned, the other inputs required from the user include the orbital elements (either mean or osculating), the reference area for the vehicle, the integration start time and date, and the vehicle mass and drag coefficient.

## CALCULATION OF REFERENCE AREAS

LTIME makes the tacit assumption that the atmospheric density does not significantly change across the dimensions of the satellite to which the reference area pertains. For most satellites this is a good assumption, but for a tethered configuration it is not. Since the density value returned from the atmospheric model refers to the density at the center of mass whose orbit is being propagated, we needed some way to account for the fact that the tether traverses an altitude range within which the density varies significantly, without constructing a new density model. We assumed that the tether would extend along a nadir line from the upper-stage. Since the drag force is linearly dependent on both the density and the area,

$$F_D = \frac{1}{2}\rho(h)V^2\left(\frac{AC_D}{m}\right) \tag{1}$$

and the density was "spoken for," we decided to artificially increase the tether area to account for the exponential increase in density. Thus we calculated the tether's effective area as

$$A_{eff}{}^T = \int_0^L w_0 e^{l/H} dl = 19.46 \ \text{m}^2 \tag{2}$$

where $w_0$ is the actual tether width (0.75 mm), L is the tether length (20 km), and H is the atmospheric density scale height (40 km).

The endmass area was calculated from a 16 x 16 inch face, with the area artificially increased by an exponential factor to account for its being in denser atmosphere than the system center of mass:

$$A_{eff}^{EM} = A^{EM} e^{L/H} = 0.27 \text{ m}^2 \tag{3}$$

(We learned from [5] after the flight that the box dimensions were not 13 x 16 x 16 inches as we had thought, but were actually 8 x 12 x 16 inches. These revised dimensions were used in the post-mortem computations.)

The Delta II Second Stage effective area was approximated assuming that the stage achieved the stable attitude illustrated in Figure 1. As seen in this figure, the endmass, tether, and upper-stage center of mass fall along a zenith-nadir line, and the upper-stage longitudinal axis was depressed 60 degrees from the direction of motion. The stage was approximated as a cylinder-cone combination, with dimensions taken from [6]. The lateral and end areas were then calculated, and the areas projected into the freestream were obtained from them.

$$A_{eff}^{\Delta} = A_{lateral} \sin(60°) + A_{end} \cos(60°) = 8.74 \text{ m}^2 \tag{4}$$

The total effective area was

$$A_{eff} = A_{eff}^{T} + A_{eff}^{EM} + A_{eff}^{\Delta} = 28.47 \text{ m}^2 \tag{5}$$

## PREFLIGHT INPUTS AND LIFETIME PREDICTIONS

In July of 1993 we performed the first set of lifetime estimates for the SEDS-2 mission, using the following inputs. The mass was taken to be 1785 kg, which included the mass of the tether, deployer, and endmass, plus the Delta II Second Stage. The drag coefficient was assumed to be 2.2, and the area was assumed to be 28.47 m$^2$. We were asked to predict lifetimes for several candidate circular orbits with altitudes of 280, 300, 310, 325, 340, 350, and 365 km. The other elements used were

| | | |
|---|---|---|
| e | = | 0.0001 |
| i | = | 28.5 deg |
| $\Omega$ | = | 334.254 deg |
| $\omega$ | = | 182.259 deg |
| M | = | 65.076 deg |

which were obtained from SEDS-1 data. The lifetimes predicted from these starting conditions were

| Initial Altitude (km) | Lifetime (days) |
|---|---|
| 280 | 8 |
| 300 | 14 |
| 310 | 18 |
| 325 | 26 |
| 340 | 37 |
| 350 | 47 |
| 365 | 68 |

In September we learned that we had overestimated the upper-stage mass. In fact the mass after the depletion burn should have been 1080.95 kg, when the mass of the SEDS-2 hardware was included. Also, by then a target orbit had been selected, with elements:

| | | |
|---|---|---|
| a | = | 6728.160 km |
| e | = | 0.00216 |
| i | = | 32.37 deg |
| $\Omega$ | = | 85.0 deg |
| $\omega$ | = | 10.0 deg |
| M | = | 0.0 deg |

Using the corrected mass and the finalized target elements, the lifetime estimated for an orbit beginning at 0 hours GMT on March 14, 1994 was 28.35 days. This was the last lifetime prediction we issued prior to the flight.

## FLIGHT DATA

We have obtained a few orbit parameters at depletion burn cutoff from [7], which are

$$h_A = 352.065 \text{ km}$$
$$h_P = 346.324 \text{ km}$$
$$i = 32.33 \text{ deg}$$

The other elements were not specifically given. We used the R.A. of the Ascending Node listed for the GPS-6 transfer orbit given in this document, 16.72 deg. For Argument of Perigee we used the value 90 deg, and for Mean Anomaly we used 180 deg. We revised the estimated endmass area to reflect the box's true dimensions; consequently the revised total effective area was 28.42 $m^2$. For deployment at 3956.58 seconds past launch time of 03:40 GMT on March 10, 1994 the predicted lifetime was 30.425 days.

According to [1], the endmass separated from the upper-stage between Rev 74 and Rev 75 on March 15, 1994, or mission day 5. The initial apogee and perigee altitudes taken from the decay history graph in this reference were 360 and 348 km, respectively. On mission day 5 of the graph, the apogee and perigee altitudes were 355 and 344 km, giving an "axis altitude" of 349.5 km.

For comparison purposes, an LTIME run using the initial altitudes and the angular elements given in the previous paragraph gave a predicted lifetime of 33.984 days. At day 5 the axis altitude was 349.489 km, so there was agreement between the tracking data and the modeled decay timelines.

Using the conditions on mission day 5 of the tracking data curve as a starting point, we developed lifetime predicitions both for the endmass plus 12 km of tether, and for the upper-stage plus 8 km of tether.

For the case of the endmass and its attached part of the tether, the box was assumed to present a 12 x 16 in rectangular face to the freestream, and the tether a 0.75 mm x 12 km rectangle. The center of mass lay 0.8 in from the center of the box face in the direction of the corner at which the tether was attached. The tether extended upward from the endmass into less dense atmosphere. Consequently the tether effective area was calculated to be

$$A_{eff}^{T12} = \int_{0km}^{12km} w_0 e^{-l/H} dl = 7.775 \text{ m}^2 \qquad (6)$$

The area of the box face was 0.134 m$^2$, so the total effective area was 7.909 m$^2$. The mass of this configuration was 29.925 kg. The question now was to specify the orbit. If we assume that the center of mass apogee and perigee were 20 km below those of the original configuration, i.e., 335 and 324 km, and that the angular elements were unchanged by the tether cut, then the predicted lifetime would be 2.813 days. Entry into such an orbit would require no recoil of the endmass/tether upon the cutting event, an eventuality that seems unlikely. To account for recoil, we assumed that the cut occurred at the apogee point, at 335 km, and that the perigee took on various values, producing the following lifetime predictions

| $h_P$ (km) | Lifetime (days) |
|---|---|
| 300 | 1.969 |
| 280 | 1.406 |
| 260 | 0.938 |
| 255 | 0.844 |
| 251 | < 0.19 |

All of these predictions seem plausible. Once the cut occurred the endmass elements would differ significantly from those of the original configuration, and they would evolve much more rapidly. It is not surprising that it was not tracked after the event.

Considering the Delta II Second Stage and its attached 8 km of tether, the stage attitude was assumed to remain pitched down 60 deg, due to the continued gravity gradient and drag forces transmitted along the tether. The stage's effective area was thus assumed to still be 8.74 m$^2$. The tether depended into denser atmosphere, and its effective area was calculated to be

$$A_{eff}^{T8} = \int_{0km}^{8km} w_0 e^{l/H} dl = 6.64 \text{ m}^2 \qquad (8)$$

giving a total effective area of 15.38 m$^2$. Assuming a revised mass of 1052.36 kg, which accounts for the lost box and tether mass, gives a lifetime prediction of 56.367 days. If the cut occurred at mission day

5.000, this gives a predicted reentry on mission day 61.367. The actual reentry occurred some time on mission day 60.

## CONCLUSION

This effort demonstrates the efficacy of LTIME as a quick-turn-around orbit lifetime predictor, and suggests that the effective area approximation scheme used here is reasonable. It should be useful in the early planning of future missions where tethers are used, if they are to be deployed for considerable lengths of time.

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DELTA II SECOND STAGE STABLE ORIENTATION

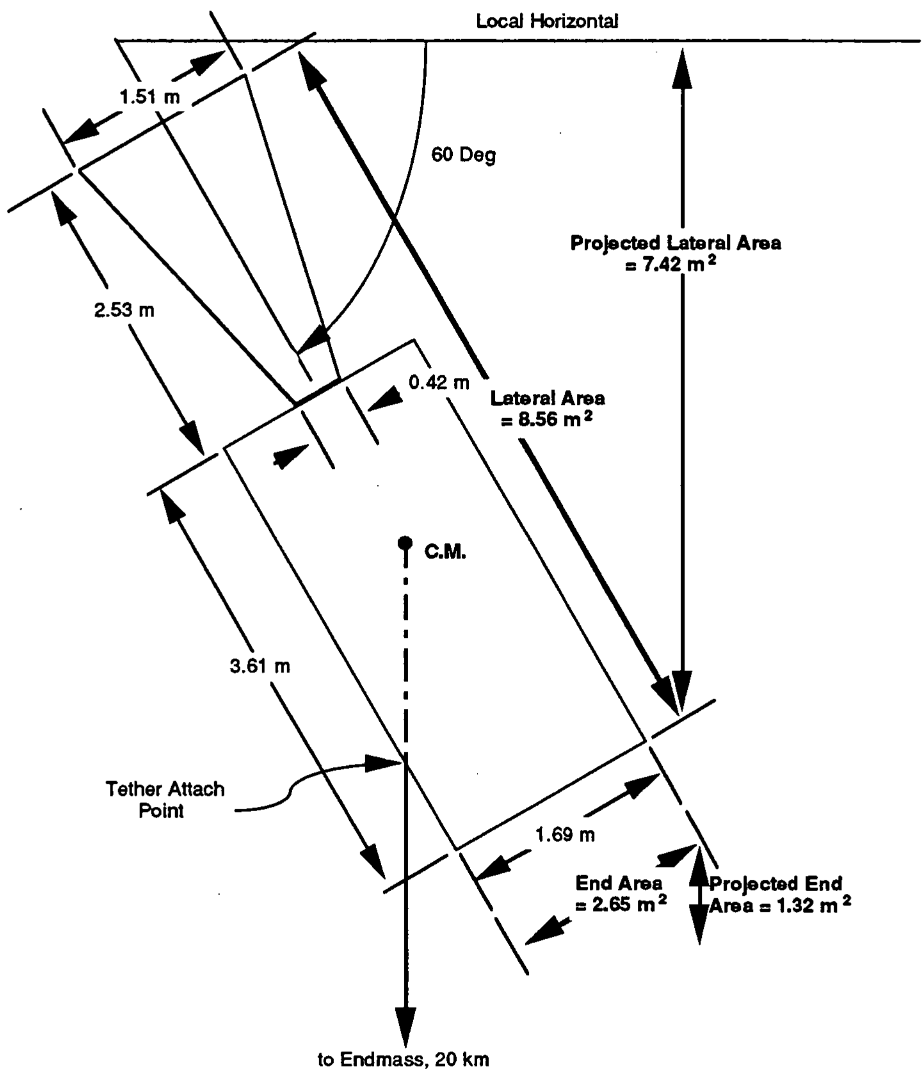


Figure 1. Approximation of Delta II Second Stage Reference Area